

5

DOUBLE-SIDED, EDGE-MOUNTED STRIPLINE SIGNAL PROCESSING MODULES AND MODULAR NETWORK

10 TECHNICAL FIELD

The present invention relates to stripline signal processing systems for radio and microwave frequency applications and, more particularly, relates to a class of double-sided, edge-mounted printed circuit (PC) modules and an associated modular network architecture for constructing stripline signal processing networks including
15 high-power analog amplifiers and beam forming networks for shaped beam and/or multi-beam antenna systems.

BACKGROUND OF THE INVENTION

Stripline signal processing circuits can be used to implement a variety of
20 analog signal operations on electromagnetic energy propagating within the circuit at radio frequency (RF) and microwave transmission frequencies. Generally stated, a stripline signal processing circuit, as that term is used in this specification, is a circuit that includes one or more transmission media segments of specified lengths and impedance characteristics, which are typically interconnected into a network, and
25 which exhibit a desired frequency response (also called a "transfer function") that performs a desired signal processing operation on electromagnetic energy propagating through the circuit. The term "microstrip" is commonly used to refer to stripline circuits having two conductors in which the transmission media segments are exposed to one or more dielectric materials on a first side backed by a conducting
30 plane and one or more dielectric materials including air on a second side without a second conducting plane. The term "tri-plate stripline" is commonly used to refer to stripline circuits that include transmission media segments are exposed to one or more dielectric materials on both sides bounded by a conducting plane on each side. In addition, the terms "air microstrip" or "air stripline" are commonly used to refer to
35 stripline circuits in which the transmission media segments are exposed to air on both

sides. All of these circuit configurations fall within the class of circuits referred to as "stripline" in this specification.

A stripline circuit often does, but does not necessarily, include one or more lumped (also called "discrete" or "conventional") electric elements, such as resistors, capacitors and inductors interconnected with the stripline segments within the circuit. These circuits may also, but need not necessarily, include active elements or stages such as active amplifier stages, and non-linear elements such as diodes, transistors, and other conventional circuit elements. In addition, these circuits may also, but need not necessarily, include other types of transmission media segments, such as coaxial cable, tubular waveguide, and so forth, as well as junctions between different types of transmission media. Because the electromagnetic energy is processed by the circuit as the signal propagates through the circuit, these circuits are typically characterized by a network of stripline segments connected between a plurality of input ports and a plurality of output ports, in which a desired signal processing operation is performed on the signal as it propagates from the input ports to the output ports.

Stripline signal processing circuits may be used to implement a wide range of functions, such as signal dividing, signal amplification, signal combining, signal encoding, and so forth. In general, they are typically used to construct relatively simple functions or modules, as described above, which are combined into more complicated structures configured to implement higher-level components, such as beam forming networks, hybrid matrix amplifiers, radio frequency amplifiers, and so forth. These higher-level components, in turn, may be interconnected and controlled to implement a wide range of commercial devices, such as radars for missiles and missile defense, satellite communication systems, wireless telephone base station antennas, Doppler radars, and many others.

Stripline signal processing circuits are typically referred to as "reciprocal" when the transfer function is the same for a signal propagating from the input ports to the output ports as it is for a signal propagating from the output ports to the input ports. Reciprocal signal processing circuits are particularly well suited for use in radar systems that both emit and receive electromagnetic energy through the same transmission path. Orthogonal signal processing circuits are a particularly important class of signal processing circuits that are characterized by a plurality of input ports that are isolated from each other. This allows the signal injected into each input port to be independently controlled without substantial interference from the other input ports. Reciprocal orthogonal circuits, even more specifically, are an important class

of signal processing circuits that are well suited to a range of applications using analog amplifiers and beam forming networks. The reciprocity property can be obtained through the reuse of a portion or all of a passive circuit for bi-directional signal flow.

5 As noted above, an orthogonal circuit includes a number of isolated input ports, and also typically includes a plurality of output ports that each receive a weighted, phase-adjusted combination of the input signals injected into the input ports. That is, the output signal at each output port typically includes a linear combination or "superposition" of input components, in which each input component is an amplitude-
10 weighted, phase-adjusted portion or division of the signal injected into one of the input ports. In other words, the input signals are isolated from each other, and each input signal is divided into a number of weighted and phase-adjusted components that are delivered to the output ports, such that each output port produces an amplitude weighted and phase-adjusted linear combination of the input signals. In addition, the
15 input and output impedances of the orthogonal circuit are typically matched across connecting junctions or ports so that the ideal non-absorbing circuit is theoretically lossless for signal flow between ports. That is, the orthogonal circuit does not absorb or reflect back any of the energy injected into the input ports, but instead divides and delivers all of the input energy to the output ports, where they are combined into
20 amplitude weighted, phase-adjusted linear combinations of the input signals.

Hybrid circuits are a subclass of orthogonal signal processing networks characterized by two inputs, two outputs, and a division of energy from each input port to the output ports. The term "hybrid junction" typically refers to a hybrid circuit in which there is an equal division of power from each input port to the output ports. A
25 "hybrid coupler," on the other hand, typically refers to a hybrid circuit in which the power division is generally unequal. A hybrid junction in which the phase shift from each input port to the two output ports is zero degrees (0°) and ninety degrees (90°), respectively, is known as a "quadrature" junction or circuit; and a hybrid junction in which the phase shift from each input port to the two output ports is zero (0°) degrees
30 and one-hundred eighty degrees (180°), respectively, is known as a "magic T" junction or circuit. These circuits are also otherwise known as $0^\circ/90^\circ$ and $0^\circ/180^\circ$ hybrids. These well known building blocks are usually reciprocal and form the basic building blocks for constructing higher-level orthogonal circuits, which are often referred to as hybrid matrices, Butler matrices, beam forming networks, hybrid matrix
35 amplifiers, RF amplifiers, duplexers, monopulse comparators, and so forth. These

building blocks can be used in conjunction with other types of junctions including non-isolating reactive tee junctions and can be used with various types of phase or time delay elements or components.

More particularly, a Butler matrix is a type of higher-level reciprocal orthogonal passive circuit characterized by an equal number of input ports and output ports, and equal power division of each input signal to the several output ports. The Butler matrix circuit provides equal power signal amplitudes delivered to each output port. A three-by-three Butler matrix includes three input ports and three output ports, a four-by-four Butler matrix includes four input ports and four output ports, an eight-by-eight Butler matrix includes eight input ports and eight output ports, and so forth. In addition, other well known circuits and circuit components can be constructed from hybrid junctions and other components such as phase shifters and resistors used for impedance matching and for analog signal processing. For example, monopulse comparators, diplexers, analog amplifiers, and beam steering circuits can be constructed in this manner. An important example of such a circuit is a high-level Butler matrix, which may be used to implement beamforming networks (BFNs) for multi-beam antenna systems with a large number of beams. These high-level Butler matrices may be constructed from complexes of four-by-four Butler matrices, which in turn may be constructed from complexes of hybrid junctions and other circuit elements, such as phase shifters.

For constructing high-level Butler matrices using hybrid junctions, see "Multiple Beams from Linear Arrays" by J.P. Shelton and K.S. Kelleher, published in the March 1961 "IRE Transactions on Antennas and Propagation." For constructing monopulse comparators using hybrid junctions, see "A Wide-Band Monopulse Comparator With Complete Nulling in All Delta Channels Throughout Sum Channel Bandwidth" by Kian Sen Ang, Yoke Choy Leong and Chee How Lee, published in the February 2003 "IEEE Transactions on Microwave Theory and Techniques." For constructing diplexer circuits using hybrid junctions, see "A Diplexer Using Hybrid Junctions" by Leon J. Ricardi published in the August 1966 "IEEE Transactions on Microwave Theory and Techniques." For constructing hybrid matrix amplifiers (HMAs) using hybrid junctions, see "Multiport Power Amplifiers For Mobile-Radio Systems Using Microstrip Butler Matrices" by A. Angelucci, P. Audagnotto, P. Corda, and B. Piovano, published in the June 1994 Antennas and Propagation Society International Symposium. Those skilled in the art will appreciate that other devices, and in particular more complicated HMAs and beam forming networks for multi-beam antenna systems, may be

constructed using the principles and techniques taught in this specification and in the documents referenced above, which are incorporated herein by reference.

In particular, hybrid junctions form the basic building blocks for the beam forming networks that are used in shaped beam and/or multi-beam antenna systems having a wide range of applications including, but not limited to, antennas for wireless telephone base stations, radars, missile guidance systems, missile defense systems, satellite surveillance systems, and satellite communication systems. In general, component beams may be pointed in different directions so to allow for substantially isolated input ports corresponding to each component beam. Component beams can be combined in various ways to form composite beams. Each beam may be encoded with beam-specific information and combining can occur for analog or digital signals.

To create these capabilities, the multi-beam antenna system includes a beam forming network or circuit that transfers signal energy from one or more input ports to a plurality of output ports operatively connected to one or more antenna elements to emit or receive the desired beams. Although the most critical design considerations may vary from application to application, it is generally desirable to manufacture beam forming networks that are inexpensive and easy to manufacture, repeatable in performance characteristics, light in weight, small in size, reliable and durable in construction, low in RF signal losses, low in noise generation, easy to ground properly, and easy to maintain. Although other design objectives may also be important in a particular application, this list includes many of the most important design considerations for many applications.

A number of these design objectives can be satisfied by manufacturing the signal processing circuits on printed circuit (PC) boards constructed from a dielectric substrate and using stripline carried on the dielectric substrate as the transmission media. The dielectric substrate typically has a ground plane attached to one side and the stripline carried on the other side. This configuration produces a circuit that can be mass produced on a PC board using conventional etching technology and processes. The resulting device exhibits low manufacturing costs, reliability, durability, repeatable performance characteristics, and accessible and solid ground characteristics. These circuits can be readily designed to exhibit low RF signal losses and low noise generation. The drawback in using this construction paradigm is that beam forming networks using hybrid junctions are often characterized by crossover points in which stripline segments must pass by each other physically without interfering with each other electrically.

On a PC board, the need for crossovers presents a design challenge because the stripline segments must remain physically separated from each other to avoid electrical interconnection (if the stripline segments physically touch each other) or radiating interference or cross-talk (if the stripline segments come too close together without physically touching each other). A number of techniques have been developed to implement crossovers for stripline signal processors implemented on PC boards, such as "flying bridge" sections of PC board that physically jump one stripline segment over another, coaxial cable links to cross each other, and multiple layered PC board constructs with conductors suspended in air and extending between PC boards to implement crossovers. Each of these designs increases the cost of the circuit, reduces the physical ruggedness of the circuit, and has the potential to increase noise generation and RF signal loss, particularly at junctions between different types of transmission media segments. More importantly, these somewhat clumsy solutions to the crossover problem greatly complicate the manufacturing process because the entire circuit cannot be arranged on a single PC board using stripline transmission media segments formed into the PC board that can then be manufactured through a conventional etching techniques and processes.

Another technique employs a circuit known as a "zero-dB crossover" that can be comprised of two cascaded quadrature hybrid junctions. Although this type of crossover can be implemented on a single flat PC board without physical trace jumps, it occupies a relatively large section of PC board space. Because the crossover is a basic building block that is repeated many times in creating a higher-level beam forming network, the significant board size required to implement the zero-dB crossover quickly multiplies into an overly large and expensive PC board as the complexity of the beam forming network increases.

In addition to the problem of crossovers, stripline signal processing circuits arranged on PC boards must maintain proper physical spacing between the stripline segments to avoid radiating interference. Further, designing each stripline segment to have a precisely determined phase characteristic at RF and microwave operational frequencies also requires the stripline circuit to be physically arranged on the printed circuit board in a manner that consumes a relatively large amount of planar board space. To maintain proper spacing and minimize the number of crossovers required, and to take advantage of the natural symmetry of the circuits, they are typically arranged out linearly, with the inputs ports spaced along one side and the output ports spaced along the other side of the stripline circuit. The transfer function of the

stripline circuit then processes the signal as it propagates across the PC board from the input ports to the output ports.

For this type of circuit configuration operating at a carrier frequency of 1.92 GHz (which is the center frequency of the authorized PCS wireless telephone band), a conventional hybrid junction layout typically occupies PC board space that is approximately one quarter of a square wavelength "in the guide" (λ_g) (e.g., an approximately square section of PC board that is $\lambda_g/2$ in length on each side). A typical dielectric material (e.g., PTFE Teflon®) having a dielectric constant equal to 2.2 ($\epsilon_r = 2.2$) can be used to construct PC boards that will exhibit an effective dielectric constant of 1.85 ($\epsilon_{\text{reff}} = 1.85$) for microstrip transmission media segments exposed to the PC board on one side and exposed to air on the other side. For this type of PC board circuit, the wavelength in the guide (λ_g) (i.e., the wavelength as propagating in the stripline transmission media as laid out on the PC board with one side exposed to the dielectric substrate and the other side exposed to air) is approximately 4.52 inches (11.48 cm), which results in a side dimension of the PC board required to implement a quadrature hybrid junction of approximately 1.13 inches (2.87 cm). It is well known to someone familiar with the art that using a substrate material having a higher dielectric constant value can reduce the overall size of the circuit. Materials with substantially higher dielectric constant values can be substantially more expensive, can have higher RF signal losses, and can have RF power handling limitations that are a lower value due to reduced stripline trace width values. It is desirable to have a circuit with sufficiently wide conducting trace width values and low RF signal loss characteristics for conditions of moderate to high operational RF power levels. Generally, the use of a substrate material with a low dielectric constant value is often desirable when RF power levels are a significant design consideration.

Using this technology and connecting four hybrid junctions together to construct a four-by-four Butler matrix occupies PC board space that is approximately one square wavelength in the guide (λ_g), which at a carrier frequency of 1.92 GHz results in a side dimension of the PC board required to implement the four-by-four Butler matrix of at least 4.52 inches (11.48 cm) using microstrip on a dielectric material having a dielectric constant equal to 2.2 ($\epsilon_r = 2.2$). The physical size of the PC board starts to become unwieldy and expensive as the number of hybrid junction elements increases beyond the eight to 16 element level. For example, a 64x64 Butler matrix requires 48 hybrid junctions and associated crossovers, and a 128x128 Butler matrix requires 160 hybrid junctions and associated crossovers. Arranging a

stripline signal processing circuit on a planar PC board in the conventional manner for these circuits would result on a very large PC board that would be very expensive to manufacture and install in a secure manner.

An approach to solving some of the problems associated with PC board stripline signal processing circuit design is provided in Tanaka et al., U.S. Patent No. 6,252,560, which describes a four-by-four Butler matrix that is arranged on a double-sided dielectric PC board with a ground plane located in the center. See Tanaka at Fig. 7. This allows the first stage hybrid junctions to be carried on a first side of the double-sided dielectric PC board, and the second stage hybrid junctions to be carried on the other side of the double-sided dielectric PC board. Crossovers are conveniently implemented using tap-through connections between the stripline circuits located on opposite sides of the PC board. This provides an elegant, low noise and space effective mechanism for implementing the crossovers. However, the circuit is still laid out linearly with the input ports located on the other side of the circuit from the output ports. In addition, the Tanaka reference shows the Butler matrix implemented on a common board with a power divider network feeding a set of patch radiators. Tanaka does not teach or suggest further steps to reduce the physical size of the Butler matrix circuit. Nor does it teach or suggest mechanisms for minimizing the PC board space required to implement higher-order analog signal processing circuits.

Accordingly, a continuing need exists for stripline signal processing networks that are inexpensive and easy to manufacture, repeatable in performance characteristics, light in weight, small in size, reliable and durable in construction, low in RF signal losses, low in noise generation, easy to ground properly, and easy to maintain. More specifically, a need exists for improvements in stripline signal processing circuit design that reduce the PC board space required to implement higher-order stripline signal processing circuits.

SUMMARY OF THE INVENTION

The present invention meets the needs described above in double-sided, edge-mounted modular printed circuit (PC) boards and an associated modular network architecture for constructing stripline signal processing networks including high-power analog amplifiers and beam forming networks (BFNs) for use in shaped beam and/or multi-beam antenna systems. Each module is manufactured from a double-sided dielectric circuit board with a ground plane located in the center. Unlike

prior double-sided PC board designs, however, the present invention includes input and output interface ports along a common interface edge defined by one or both sides of the double-sided circuit board. This allows non-crossing circuit portions to be carried on each side of the double-sided circuit board, with crossovers implemented with tap-through connections between the circuit portions, and input-output ports located along the interface edge, to create an edge-mounted system for constructing modular signal processing networks from a system of double-sided, edge-mounted modules.

Typically, a first stage of the circuit extends linearly away from input ports located at the interface edge, tap-through connectors participate in the implementation of crossovers to a second stage of the circuit located on the other side of the double-sided PC board. The second stage circuit then extends back toward output ports, which are also located at the interface edge. In this manner, the first and second stages of the circuit overly each other on opposite sides of the double-sided PC board, and all input and output ports are located along a common interface edge. In addition, the circuit portions themselves, typically hybrid junctions and circuit portions that include complexes of hybrid junctions, may include sinuous stripline trace elements that reduce the length of the PC board in a desired dimension. For example, first and second stage complexes of hybrid junctions may be laid out using sinuous trace elements to minimize the depth of the PC board extending away from the interface edge.

The results is a compact, edge-mounted, double-sided, modular signal processing PC board design that is well suited to assembling higher-order circuits from complexes of lower-order, edge-mounted modules. This architecture may be used to construct hybrid matrix amplifiers (HMAs) and beam forming networks for multi-beam antenna systems that exhibit many advantages over prior HMA and beam forming networks including decreased size, decreased cost, standardization of module design, scalability, repeatability of manufactured products, ease of construction, and ease of repair and maintenance. Circuit configurations implemented in this manner can also be readily configured to exhibit low noise generation, low power and signal losses, and rugged physical construction.

Generally described, the invention may be implemented as a stripline signal processing module that includes a first planar dielectric substrate that defines an edge, a second planar dielectric substrate that defines an edge, and a ground plane. The first dielectric substrate, the second dielectric substrate, and the ground plane are

adhered together in an overlaying configuration with the ground plane located between the first and second dielectric substrates and the edges aligned to form an interface edge. A first stripline circuit is carried on the first dielectric substrate, and a second stripline circuit is carried on the second dielectric substrate. The module also includes one or more input ports and one or more output ports located at the interface edge and electrically connected to the first or second stripline circuits. The first and second stripline circuits are configured to receive propagating signals at the input ports, perform a signal processing operation on the received propagating signals, and deliver processed signals to the output ports.

Typically, the first dielectric substrate, the second dielectric substrate, and the ground plane are approximately coextensive in their planar dimensions to form a double-sided dielectric PC board with a conducting ground plane sandwiched in the middle. In addition, the first and second stripline circuits are typically constructed from stripline that is exposed to the dielectric substrate on one side and exposed to air on the opposite side. The module may also include one or more electrical connections between the first and second stripline circuits, which are typically implemented as tap-through connectors passing through and insulated from the ground plane. Further, the first and second stripline circuits may be non-crossing, and the electrical connections between the stripline circuits may participate in the formation of crossovers connecting the stripline circuits to form orthogonal signal processing circuits, such as circuits comprised of hybrid junctions.

In particular, the first and second stripline circuits may implement first and second stage orthogonal beam forming networks, respectively, that are combined to form a multi-stage orthogonal beam forming network. For example, the multi-stage orthogonal beam forming network may be a two-by-four beam steering circuit, a diplexer filter circuit with at least three ports, a three-by-three Butler matrix circuit, a four-by-four Butler matrix circuit, an eight-by-eight Butler matrix circuit, a four-by-four monopulse comparator circuit, a three-by-four monopulse comparator circuit, an eight-by-eight monopulse comparator circuit, or a three-by-twelve monopulse comparator circuit, and other like constructions. These modules may then be combined to construct higher-order machines, such as HMAs and beam forming networks for shaped beam and/or multi-beam antennas.

For all of these modules, the stripline circuits may include one or more sinuous trace legs configured to exhibit a desired phase and impedance characteristic while reducing the displacement of the trace in a selected dimension. For example, the first

and second stripline circuits may implement a four-by-four Butler matrix circuit configured for an operational carrier frequency, in which the planar dimensions of the first dielectric substrate, the second dielectric substrate, and the ground plane are less than one and one-half times the wavelength of the carrier frequency in the strip transmission media. More specifically, the planar dimensions may include a length dimension in the direction of the interface edge that is less than one and one-half times the wavelength of the carrier frequency in the guide; and a width dimension perpendicular to the interface edge that is less than one-half times the wavelength of the carrier frequency in the guide. Even more particularly, the length may be approximately equal to the wavelength of the carrier frequency in the strip transmission media, and the width may be approximately one-fourth times the wavelength of the carrier frequency in the strip transmission media.

The invention may also be embodied as a modular stripline signal processing network including an interconnected set of network modules, in which each network module includes a first stripline circuit located on a first side of a double-sided dielectric substrate board, a second stripline circuit located on a second side of the double-sided dielectric substrate board, and one or more input ports and output ports located along an interface edge defined by the dielectric substrate board. In this case, each network module is configured to receive propagating signals at the input ports, perform a signal processing operation on the received propagating signals, and deliver processed signals to the output ports.

The interface ports for each network module, as described above, may be edge-connected to another network board through soldered connections. Alternatively, they may be configured for removable edge-connection to another network board through separable connections, for example by implementing the interface ports as blind-mate coaxial connectors. Typically, each network module implements a lower-order hybrid junction circuit, and the interconnected set of network modules combines the network modules to implement a higher-order hybrid junction circuit. For example, each lower-order hybrid junction circuit may be a three-by-three, a four-by-four, or an eight-by-eight Butler matrix circuit. And the higher-order hybrid junction circuit may include at least sixteen input ports and sixteen output ports. For example, the higher-order hybrid junction circuit may be a 64x64 or 128x128 Butler matrix used as a beam forming network for a multi-beam antenna. Alternatively, the higher-order hybrid junction circuit may be a multi-stage high-power HMA including scores of hybrid junctions. Many other end products may be

constructed using the modular, edge-connected, double-sided dielectric PC board configuration enabled by the present invention.

In view of the foregoing, it will be appreciated that the present invention avoids the drawbacks of prior methods for implementing stripline signal processing circuits, such as analog amplifiers and beam forming networks, on PC boards. The specific techniques and structures for creating stripline signal processing modules, and higher-order modular signal processing networks constructed from complexes of lower-order network modules, and thereby accomplishing the advantages described above, will become apparent from the following detailed description of the embodiments and the appended drawings and claims.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1 is a block diagram of a multi-beam antenna system including a modular beam forming network embodying the present invention.

FIG. 2 is a block diagram of a vertical electrical downtilt antenna system including a modular beam forming network embodying the present invention.

FIG. 3A is a perspective view of a conceptual design for a double-sided, edge-mounted stripline signal processing module.

FIG. 3B is a perspective view of an alternate conceptual design for a double-sided, edge-mounted stripline signal processing module.

FIG. 4 is a perspective exploded view of a double-sided, edge-mounted stripline signal processing module.

FIG. 5A is a functional block diagram of a two-by-four beam forming network for use in a single-beam vertical electrical downtilt antenna system.

FIG. 5B is a circuit board layout diagram of the back side portion of a double-sided, edge-mounted stripline signal processing module implementing the two-by-four beam forming network shown in FIG. 5A.

FIG. 5C is a circuit board layout diagram of the front side portion of the two-by-four beam forming module shown in FIG. 6A.

FIG. 6A is a functional block diagram of an alternate embodiment of a two-by-four beam forming network for use in a single-beam vertical electrical downtilt antenna system.

FIG. 6B is a circuit board layout diagram of the back side portion of a double-sided, edge-mounted stripline signal processing module implementing the two-by-four beam forming network shown in FIG. 6A.

FIG. 6C is a circuit board layout diagram of the front side portion of the two-by-four beam forming network filter module shown in FIG. 6A.

FIG. 7A is a functional block diagram of a four-by-four Butler matrix module.

5 FIG. 7B is a circuit board layout diagram of the back side portion of a double-sided, edge-mounted stripline signal processing module implementing the four-by-four Butler matrix circuit shown in FIG. 7A.

FIG. 7C is a circuit board layout diagram of the front side portion of the four-by-four Butler matrix module shown in FIG. 7A.

FIG. 8A is a functional block diagram of a monopulse comparator module.

10 FIG. 8B is a circuit board layout diagram of the back side portion of a double-sided, edge-mounted analog signal processing module implementing the monopulse comparator module shown in FIG. 8A.

FIG. 8C is a circuit board layout diagram of the front side portion of the monopulse comparator module shown in FIG. 8A.

15 FIG. 9 is a functional block diagram of an eight-by-eight Butler matrix module.

FIG. 10A is a circuit board layout diagram of the back side portion of a double-sided, edge-mounted analog signal processing module implementing the eight-by-eight Butler matrix circuit shown in FIG. 9.

20 FIG. 10B is a circuit board layout diagram of the front side portion of the eight-by-eight Butler matrix module shown in FIG. 9.

FIG. 11A is a conceptual diagram of an edge-mounted modular stripline signal processing network for implementing an eight-by-eight Butler matrix from two four-by-four Butler matrix modules and a third module implementing four hybrid junctions that are each daughter boards edge mounted to a mother board.

25 FIG. 11B is a functional block diagram of an eight-by-eight Butler matrix illustrating the division of signal processing functions among the modules shown in FIG. 11A.

FIG. 12 is a conceptual diagram of tree-type stripline signal processing network comprising a system of daughter boards edge mounted to mother boards.

30 FIG. 13 illustrates a modular stripline signal processing network including daughter boards edge mounted to a mother board using separable blind-mate coaxial connectors.

FIG. 14 is a logic flow diagram illustrating a process for designing a modular stripline signal processing network.

FIG. 15A is a perspective exploded view of a tri-plate stripline module for a modular stripline signal processing network.

FIG. 15B is a side view of a first stripline circuit of the tri-plate stripline module of FIG. 15A.

5 FIG. 15C is a side view of a second stripline circuit of the tri-plate stripline module of FIG. 15A.

FIG. 15D is an assembled perspective view of the tri-plate stripline of FIG. 15A.

FIG. 16A is a functional block diagram of a diplexer filter module.

10 FIG. 16B is a circuit board layout diagram of the back side portion of a double-sided, edge-mounted analog signal processing module implementing the diplexer filter module shown in FIG. 8A.

FIG. 16C is a circuit board layout diagram of the front side portion of the diplexer filter module shown in FIG. 16A.

15 DETAILED DESCRIPTION OF THE EMBODIMENTS

The present invention relates to a class of double-sided, edge-mounted printed circuit (PC) modules and an associated modular network architecture for constructing stripline signal processing networks including high-power analog amplifiers and beam forming networks for use in multi-beam antenna systems. The stripline signal processing networks are characterized by network elements constructed from defined-length segments of stripline configured to exhibit precisely determined phase and impedance characteristics. These circuits may also include conventional passive "lumped" electrical elements, such as resistors, capacitors and inductors; non-linear circuit elements such as diodes; and active electrical elements, such as amplifiers and transistors.

20 The stripline segments are typically constructed from conductive stripline, such as tin-covered copper traces, carried on a dielectric PC board substrate constructed from, for example, PTFE Teflon® laminate impregnated with glass fibers. Although other types of dielectric PC board substrates may be used, this particular substrate exhibits desirable dielectric, cost, hardness, durability, consistency and etching characteristics that makes it well suited to mass producing PC boards for relatively low cost, high-production applications, such as wireless telephone base station antennas and similar applications. A double-sided PC board can be readily manufactured by using a dielectric adhesive layer to adhere a first PC board carrying an attached ground plane to a second PC board without an attached ground plane to

35

create an integral double-sided dielectric PC board with a ground plane sandwiched in the middle.

Large planar sheets of this material may then be mass produced, etched and cut into multiple PC boards or modules in which each resulting module has two sides of dielectric PC board, each carrying an etched stripline circuit, and a center ground plane. Typically, the dielectric PC board sides and the center ground plane are cut with a common die, and as a result are substantially coextensive in planar dimensions. For many applications, the stripline circuits on each side of the board may be non-crossing and formed entirely of etched stripline, which avoids the need for coaxial links, "flying bridge", "air bridge", "zero dB crossover", or other devices to implement crossovers that might add noise, increase size, cost and fragility to the board. Connections between stripline circuits located on either side of the board are typically implemented through tap-through connectors, and the input and output ports are located along a common interface edge. In addition, for some applications the modules may include connection points for solder-mounting discrete electrical elements, such as resistors, capacitors, inductors, diodes, transistors, and amplifiers into the stripline circuits.

A variety of standard and special purpose "lower-level" modules, such as quadrature hybrids, diplexer filters, amplifier power dividers, amplifier crossovers, monopulse comparators, Butler matrix circuits, and customized beam forming networks may be constructed in bulk this manner. These modular components may then be assembled together in an edge-mounted "tree" configuration to create higher-level stripline signal processing machines, such as high-power hybrid matrix amplifiers, other types of RF amplifiers, beam forming networks for multi-beam antenna systems.

In particular, lower-level orthogonal circuit modules with well-known properties, such as Butler matrices, quadrature hybrids, "magic-T" hybrids, and monopulse comparators may be mass produced inexpensively, with tight performance tolerances, and with desirable size, ruggedness and durability qualities. These basic building blocks of bi-directional signal processing systems implemented in double-sided, edge-mounted modules may then be assembled to construct higher-order signal processing networks. These higher-order networks, in turn, provide the signal processing network infrastructure required to assemble a wide range of commercially and scientifically important high-power and multi-beams systems, such as multi-beam Doppler radar systems, multi-beam missile defense systems, missile guidance

systems, satellite reconnaissance systems, satellite communication systems, and the like. Those skilled in the art will appreciate that the standardization of the basic building blocks of orthogonal signal processing systems into double-sided, edge-mounted modules that can be inexpensively mass produced and readily assembled
5 into higher-order signal processing machines represents a major advance in this particular technology.

Further, the modular design of complex multi-beam and high-power amplifier using standardized double-sided, edge-mounted modules with non-crossing stripline circuits on each side of the PC board and cross-board connections implemented
10 through tap-through connectors exhibit other desirable design characteristics. For example, the modules may be edge-connected together with separable connectors, such as blind-mate coaxial connection to allow easy removal and replacement of individual components. The "tree" nature of edge-connected module construction produces a three-dimensional processing unit, as opposed to a huge planar
15 configuration, which is easier to move and install, reduces the required bracing, reduces the weight, reduces wind and drag concerns for outdoor installations, and provides inherent ventilation corridors within the three-dimensional processing unit. Basically, the double-sided, edge-mounted modular allows much more processing capability to be manufactured and installed, much less expensively, within in any
20 given physical envelope.

In addition, the conducting ground plane located in the middle of the double-sided dielectric board isolates the circuits on either side of the board from radiating interference from each other, which allows the circuits to be located close to each other in space yet maintain electric isolation. The ability to deploy the stripline circuits
25 in each side of the board in non-crossing configurations, which crossovers implemented with tap-through connections, produces a low-noise, low-loss and rugged board design. The use of edge-connected I/O further reduces the cost and simplifies the design of the modular systems by avoiding the need for free spans of conductors, coaxial cable or other types of links between boards other than the edge
30 connections located at edge-mounted junctions between boards.

The inventor of the present system has also developed a technique for using sinuous stripline traces to reduce the size of modules in a desired planar dimension. This innovation, combined with the double-sided, edge-mounted board design, enables compaction of planar stripline signal processing PC board circuits to an
35 extent that has not been achieved before for circuit constructions using low dielectric

constant substrate materials. For a particular example, the conductive stripline transmission media segments may be formed into the PC board using a conventional PC board etching technique. The PTFE Teflon® dielectric material exhibits a dielectric constant equal to 2.2 ($\epsilon_r = 2.2$), which results in stripline segments exposed to the PC board on one side and exposed to air on the other side exhibiting an effective dielectric constant of 1.85 ($\epsilon_r = 1.85$). For this type of PC board circuit operating at a carrier frequency of 1.92 GHz (the center of the authorized PCS wireless telephone band), the wavelength in the guide (λ_g) (i.e., the wavelength as propagating in the stripline as carried on the PC board with one side of the stripline exposed to the dielectric substrate and the other side exposed to air) is approximately 4.52 inches (11.48 cm), which results in a side dimension of the PC board required to implement a hybrid junction in a conventional planar layout of approximately 2.26 inches (5.74 cm). Using planar technology and connecting four hybrid junctions together to construct a four-by-four Butler matrix occupies PC board space that is approximately one square wavelength in the guide (λ_g), which results in a side dimension of the PC board required to implement the four-by-four Butler matrix of 4.52 inches (11.48 cm). It will be appreciated that the wavelengths change for different carrier frequencies and for PC board substrates with different dielectric constant values, for surrounding media other than air, and for configurations in which a dielectric material is located on both sides of the stripline circuit, which could be implemented for the entire board or for selected segments. For this reason, the board dimensions are preferably expressed as multiples of λ_g rather than absolute lengths.

Using the sinuous stripline traces combined with the double-sided, edge-mounted board design allows a four-by-four Butler matrix to be implemented on a board that is approximately λ_g (i.e., 4.52 inches or 11.48 cm) along the interface edge, but is only $\lambda_g/4$ (i.e., 1.13 inches or 2.27 cm) in the direction extending away from the interface edge. This represents a reduction to one-fourth the board size of that required to implement the four-by-four Butler matrix using the conventional layout. For a mass-produced, highly price sensitive item, such as wireless telephone base station antennas, this reduction in board size alone represents a significant cost advantage. This advantage, together with the other benefits of the modular design, including the elegant, low-noise, low-loss crossover implementation through tap-through connections, low cost, small size, low weight, and ease of manufacturing result in a major improvement in stripline signal processing circuit design.

Turning now to the figures, in which similar reference numerals indicate similar elements in the several figures, Fig. 1 is a block diagram of a multi-beam antenna system **100** including a modular beam forming network **102** embodying the present invention. As noted above, many different types of stripline signal processing modules and modular systems may be constructed using the double-sided, edge mounted PC board modular technology of the present invention. Multi-beam antenna systems are an important class of these systems, which can be used to drive wireless base station antennas, Doppler radar systems, satellite communication systems, missile defense and guidance systems, and a range of other devices that are generally characterized by a plurality of voltage sources **104** feeding a modular, double-sided, edge-mounted stripline beam forming network **102**, which in turn drives an antenna array **106** to produce multiple beams **108**. In general, each of these beams may include a beam component from each of the voltage sources **104**, and may be independently steered and encoded with information. Also, each of these beams may be combined to form one or more composite beams that can produce a "shaped beam" coverage pattern.

FIG. 2 is a block diagram of a vertical electrical downtilt ("VED") antenna system **200**, which is a simplified single-beam variant similar to the multi-beam antenna system **100**. This system includes a pair of complementary voltage sources **204** that typically produce in-phase voltage signals that vary in magnitude inversely in proportion to each other. That is, the voltage sources **204a** and **204b** are typically in phase with each other throughout the range of control, and the amplitude of voltage source **204a** increases proportionately as the amplitude of voltage source **204b** decreases, and vice versa, in a complementary fashion throughout the range of control. Typically, this type of complementary voltage source pair can be generated by splitting a single constant-amplitude voltage signal into two channels and varying the power division between the two channels. The pair of complementary voltage sources **204** feeds a modular, double-sided, edge-mounted vertical electrical downtilt network **202**. This network produces antenna drive signals that cause an antenna array **206** to generate a single beam **208** propagating in a direction that tilts downward and upward in response to changes in the voltage division between the voltage sources **204a** and **204b**. For example, the beam **208** may be at its highest pointing direction **208a** when all of the drive power is directed through the voltage source **204a**, may be at its lowest pointing direction **208b** when all of the drive power is directed through the voltage source **204b**, may be at a central pointing direction **208c** when the drive

power is divided equally between the voltage sources **204a** and **208b**, and may vary smoothly between these pointing directions as the power division through the voltage sources **204a** and **208b** is varied smoothly.

FIG. 3A is a perspective view of a conceptual design for a double-sided, edge-mounted stripline signal processing module **300**. This particular example includes a first dielectric PC board **302** with an integral ground plane **304** adhered to a second dielectric PC board **306** by a dielectric adhesive **308**. The planar dimensions of the PC board dielectric substrate sides **302**, **306** are coextensive with the common ground plane **304** layer to create a double-sided dielectric PC board with a common ground plane sandwiched in the middle. Edge connectors **310** are located along a common interface edge **312** to permit edge mounting of the module **300** to a socket or another PC board. The first side **302** of the double-sided dielectric PC board carries a first stripline circuit **314**, typically a conductive stripline formed into the PC board through a conventional etching process. Similarly, the second side **306** of the double-sided dielectric PC board carries a second stripline circuit **316**, again a conductive stripline formed into the PC board through a conventional etching process. As needed, the first and second stripline circuits **314**, **316** are connected to the ground plane **304** layer with ground connections. The stripline circuits **314**, **316** may also be connected to each other with one or more tap-through connectors **318** that pass through, but are electrically isolated from, the ground plane **304** layer. However, a designer could wrap a connector around an edge of the board to create a less elegant but functional electrical connection between the first and second stripline circuits **314**, **316**.

As discussed previously, in certain embodiments the first and second stripline circuits **314**, **316** are non-crossing, and the tap-through connectors **318** participate in the implementation of crossovers to implement a hybrid coupler, hybrid junction, hybrid matrix, or other orthogonal signal processing module characterized by low-level hybrid components connected together through crossovers to create a higher-level circuit. For example, non-crossing first stage hybrid junctions of a four-by four Butler matrix may be implemented on the first side **302** of the double-sided PC board **300**. These first stage hybrid junctions include input ports located along the interface edge **312**, and circuits are laid out to extend away from the interface edge. The second stage hybrid junctions of the four-by four Butler matrix are then implemented on the second side **306** of the board **300** and interconnect with the first stage hybrid junctions through crossovers located away from the interface edge **312**. The second

stage hybrid junctions then run back toward the interface edge **312**, where they terminate at output ports located along the interface edge. The crossovers required to connect the first and second stage hybrid junctions into the four-by four Butler may be implemented through a combination of tap-through connectors **318** and strategic positioning or overlaying of the first and second stripline circuits **314**, **316** with respect to each other. This creates a compact, ruggedly constructed, double-sided, edge-mounted four-by-four Butler matrix module, with all eight inputs and output ports located along the interface edge.

FIG. 3B is a perspective view of an alternate conceptual design for a double-sided, edge-mounted stripline signal processing module **320**. This module is similar to the module **300** described with reference to FIG. 3A except that the interface edge **312'** is formed from only a single side **306'** of the double-sided PC board. The interface ports may be located on both faces of the PC board **306'** as shown in FIG. 3B, or they may all be located on one face, in accordance with the manufacturer's design preference.

FIG. 4 is a perspective exploded view of a double-sided, edge-mounted stripline signal processing module **400**. The previously-described elements including a front-side circuit portion **402**, a back-side circuit portion **404**, a ground plane **406**, edge input and output ports **408**, ground connections **410**, and a tap-through connector **412** passing through but electrically isolated from the common ground plane **406** are shown in an exploded manner for clarity.

FIG. 5A is a functional block diagram of a two-by-four beam forming network **500** that may be used to implement the single-beam vertical electrical downtilt network **206** shown in FIG. 2. The functional block diagram is equivalent to a conventional four-by-four Butler matrix beam forming network with two of the inputs terminated into impedance load resistors R_1 and R_2 . The elements **502** and **504** represent first stage two-by-two quadrature (as indicated by the "0/90°" designation) hybrid junction components. The elements **505** and **506** represent second stage two-by-two quadrature hybrid junction components, and the elements **510** and **512** represent crossovers. There are four output ports (out_1 - out_4) but two input ports (in_1 and in_2) because the unnecessary additional inputs are shunted to ground through impedance matching resistors $R1$ and $R2$, as shown in the schematic diagram.

FIG. 5B is a circuit board layout diagram of the back side circuit portion of a double-sided, edge-mounted, stripline signal processing module **520** for implementing the two-by-four beam forming network **500** shown in FIG. 5A. The second stage

hybrid junction **506** is implemented with sinuous trace elements **522**, and the second stage hybrid junction **508** is implemented with similar sinuous trace elements **524**, to reduce the linear board length running away from the interface **526**. FIG. 5C shows the circuit board layout diagram of the front side circuit portion of the board **530**, which carries the first stage hybrid junctions **502** and **504** having similar sinuous trace elements. The commonly labeled tap points (A, B, C, etc.) indicate the locations of tap-through connectors connecting the front and back side circuit portions, and the input and output ports are labeled. The front and back side portions are brought together with the interface edges aligned in a double-sided, edge-mounted configuration. In addition, FIGS. 5B and 5C are laid out with respect to each other to show the circuit diagrams in a butterfly manner.

The approximate board dimensions of λ_g along the interface edge **526** and $\lambda_g/4$ in the direction running away from the interface edge are shown on FIGS. 5B and 5C. For a PC board manufactured from PTFE Teflon® dielectric material exhibiting a dielectric constant equal to 2.2 ($\epsilon_r = 2.2$), which results in stripline transmission media segments exposed to the PC board on one side and exposed to air on the other side exhibiting an effective dielectric constant of 1.85 ($\epsilon_{\text{reff}} = 1.85$). This circuit board design may be implemented for a carrier frequency of 1.92 GHz on a double-sided, edge-mounted PC board module that is approximately λ_g (i.e., 4.52 inches or 11.48) cm along the interface edge, and is $\lambda_g/4$ (i.e., 1.13 inches or 2.27 cm) in the direction extending away from the interface edge.

FIG. 6A is a functional block diagram of a two-by-four beam forming circuit **600**, which includes two-by-two quadrature hybrid junctions **602** and **604**, along with crossovers **606** and **608**. FIG. 6B is a circuit board layout diagram of a back side portion of a double-sided, edge-mounted stripline signal processing module **610** implementing the two-by-four beam forming circuit shown in FIG. 6A, and FIG. 6C is a circuit board layout diagram of the front side portion **620** of that circuit. The beam forming circuit **600** can be implemented on a PC board module constructed from the same materials and having the same dimensions as the two-by-four beam forming network **500** described above with reference to FIGS. 5A-C. In other words, these circuits may be manufactured in an identical manner except that the stripline circuitry is slightly different, as appropriate to implement a different circuit.

FIG. 7A is a functional block diagram of a four-by-four Butler matrix beam forming module **700**, which includes first stage two-by-two quadrature hybrid junctions **702** and **704**, second stage two-by-two quadrature hybrid junctions **706** and **708**,

phase shifters **710** and **712**, and crossovers **714** and **716**. FIG. 7B is a circuit board layout diagram of the back side of a double-sided, edge-mounted stripline signal processing module **720** implementing the four-by-four Butler matrix shown in FIG. 7A, and FIG. 7C is the circuit board layout diagram of the back side **722** of that circuit.

5 The four-by-four Butler matrix **700** can be implemented on a PC board module constructed from the same materials and having the same dimensions as the two-by-four beam forming networks **500** and **600** described above with reference to FIGS. 5A-C and FIGS. 6A-C, respectively.

FIG. 8A is a functional block diagram of a four-by-four monopulse comparator module **800**, which includes first stage two-by-two quadrature hybrid junctions **802** and **804**, second stage quadrature hybrid junctions **806** and **808**, and crossovers **810** and **812**. The hybrid junctions **802** and **804** are used in combination with phase offset shifters **812** and **814** to effectively to produce the functional equivalent characteristics of a two-by-two "magic-T" ($0^\circ/180^\circ$) hybrid junction. It is well known to those familiar with the art that, for example, a "rat-race" $0^\circ/180^\circ$ hybrid junction can be used in place of the hybrid junction **802** and phase offset shifter **812**. FIG. 8B is a circuit board layout diagram of the back side portion of a double-sided, edge-mounted stripline signal processing module **820** implementing the four-by-four monopulse comparator circuit shown in FIG. 8A, and FIG. 8C is the circuit board layout diagram of the front side **822** portion of that circuit. The four-by-four monopulse comparator circuit **800** can be implemented on a PC board module constructed from the same materials and having the same dimensions as the two-by-four beam forming networks **500** and **600** described above with reference to FIGS. 5A-C and FIGS. 6A-C, respectively, and the four-by-four Butler matrix **700** described above with reference to FIGS. 7A-C.

FIG. 9 is a functional block diagram of an eight-by-eight Butler matrix module **900**, which includes a first stage **902** including a first four-by-four "quasi-Butler" matrix **904** and a second four-by-four "quasi-Butler" matrix **906**. The circuit **900** also includes a second stage **908** including four hybrid junctions **910a-d**. The first "quasi-Butler" matrix **904** includes first stage quadrature hybrid junctions **912** and **914**, second stage quadrature hybrid junctions **916** and **918**, a crossover **920**, and a 67.5° phase offset shifter **921**, and a 22.5° phase offset shifter **936**. Similarly, the second "quasi-Butler" matrix **906** includes first stage quadrature hybrid junctions **922** and **924**, second stage quadrature hybrid junctions **926** and **928**, a crossover **930**, and a 67.5° phase offset shifter **931**, and a 22.5° phase offset shifter **937**. Additional crossovers

940 and **942** and 45° phase shifters **932,934, 935,** and **924** connect the first stage **902** to the second stage **908**, with further crossovers **944, 946, 948,** and **950** connecting the hybrid junctions of the second stage **908** to the output ports.

FIG. 10A is a circuit board layout diagram of the back side circuit portion **1000** of a double-sided, edge-mounted stripline signal processing module implementing the eight-by-eight Butler matrix circuit shown in FIG. 9, and FIG. 10B shows the front side circuit portion of that module. As in the previous double-sided circuit board illustrations, FIGS. 10A and 10B are illustrated in a butterfly manner with common designation (e.g., A, B, C, etc.) identifying the tap-through connectors, which typically participate in the implementation of the crossovers. FIGS. 10A-10B also illustrate the use of sinuous trace legs, as exemplified by the sinuous trace leg **1004**, to reduce the board size in the direction extending away from the interface edge **1006**. The planar board dimensions in multiples of λ_g are also shown.

FIG. 11A is a conceptual diagram of an edge-mounted modular stripline signal processing network **1100** for implementing an eight-by-eight Butler matrix from two four-by-four "quasi-Butler" matrix modules **1102** and **1104** and a third module **1106** implementing four hybrid junctions edge connected to a motherboard **1108**. Of course, one or more of these modules, or additional functionality, could be implemented on the motherboard **1108**. FIG. 11B is a functional block diagram of an eight-by-eight Butler matrix similar to the diagram of FIG. 9, but in this example illustrating how the signal processing functions are divided among the modules shown in FIG. 11A. Specifically, the first four-by-four "quasi-Butler" matrix **904** is implemented on the first module **1102**, the second four-by-four "quasi-Butler" matrix **906** is implemented on the second module **1104**, and the four hybrid junctions of the second stage **908** are implemented on the first module **1106**. These three modules are edge-mounted to and interconnected through the motherboard **1108** to provide a multi-module alternative for implementing the same eight-by-eight Butler matrix described with reference to FIGS. 10A-10C, which is implemented as a single double-sided, edge-mounted planar module.

FIG. 12 is a conceptual diagram of tree-type stripline signal processing network **1200** comprising a "tree" type system of daughter boards **1204, 1206, 1208, 1210,** and **1212** edge mounted to a mother board **1202**. That is, the modular signal processing architecture illustrated at a relatively simple level in FIGS. 11A-11B may be extended in a straightforward manner to create more complex processing systems to drive higher-order networks, such as a 64-by-64 Butler matrix, 128-by-128 Butler

matrix, a multi-level high-power hybrid matrix amplifier, and so forth. These stripline signal processing engines, in turn, provide the signal processing infrastructure for complex systems, such as multi-beam Doppler radars, multi-beam missile tracking and defense systems, multi-beam satellite reconnaissance systems, and many other devices employing the modular signal processing architecture illustrated by the exemplary embodiments of the invention described above.

FIG. 13 illustrates a modular stripline signal processing network **1300** including daughter boards **1302**, **1304**, and **1306** edge mounted to mother board **1308** using separable blind-mate coaxial connectors exemplified by the connector **1310**, **1320**.

Using separable connectors **1310** and **1312** to connect the boards together facilitates installation and removal of the boards for modular construction and maintenance purposes. It will be appreciated that additional support structures, such as side rail supports and board lock-down mechanisms, as are well known in the art, may be employed to increase the physical integrity of the constructed unit.

FIG. 14 is a logic flow diagram illustrating a process **1400** for designing a modular stripline signal processing network. The following description will refer to the four-board structure implementing the eight-by-eight Butler matrix shown in FIGS. 11A-B as a simple but illustrative example of the network design process. In step **1402**, the circuit designer defines the requirements of the network, such as an eight-by-eight Butler matrix for the example shown in FIGS. 11A-B. Step **1402** is followed by step **1404**, in which the circuit designer breaks down the overall network into zones. In the eight-by-eight Butler matrix example shown in FIGS. 11A-B, these zones include the first four-by-four "quasi-Butler" matrix **904** as a first zone, the second four-by-four "quasi-Butler" matrix **906** as a second zone, and the four hybrid junctions **908** as a third zone. Step **1404** is followed by step **1406**, in which the circuit designer defines modules to implement the zones that are properly sized for the desired module sizes. Step **1406** is followed by step **1408**, in which the circuit designer designs front and back circuit portions, along with tap-through connections as appropriate, that overlay each other to implement the circuits in a double-sided manner, preferably with non-crossing circuit portions on each side of the board. Step **1408** is followed by step **1410**, in which the circuit designer designs the modules to implement the required functionality while meeting applicable module constraints.

This result of this process is illustrated by the modular board design shown in FIGS. 5A-C, 6A-C, 7A-C, 8A-C, and 10A-B, in which each module is laid out in a double-sided, edge-connected format employing non-crossing circuit portions on each

side of the board and tap-through connections to implement crossovers. Step **1410** is followed by step **1412**, in which the circuit designer designs the modular assembly. In the eight-by-eight Butler matrix for the example shown in FIGS. 11A-B, this corresponds to edge connecting the modules **1102**, **1104** and **1106** to the mother board **1108** to create a complete modular design. It will be appreciated that the four-board modular design of the eight-by-eight Butler matrix shown in FIGS. 11A-B is but one relatively simple example of a design technique enabled by the present invention that may be used design and construct a wide range of stripline signal processing machines within the class of double-sided, edge-mounted printed circuit (PC) modules and the associated modular network architecture.

The stripline modules described above with reference to FIGS. 3A-10B are of the type commonly referred to as "microstrip," in which the stripline transmission media segments are exposed to a dielectric material on one side and air on the other. It should be understood that any of the stripline circuits described in this specification may alternatively be configured as tri-plate stripline modules, in which the stripline transmission media segments are exposed to a dielectric material on both sides. This is typically accomplished by adding dielectric covers with outer ground plates over the air-exposed stripline circuits of the microstrip configurations. The result is a multi-layer double-sided stripline module including a first outer ground plane layer, followed by a dielectric layer, followed by a first stripline circuit layer, followed by a dielectric layer, followed by a center ground plane layer, followed by a dielectric layer, followed by a second stripline circuit layer, followed by a dielectric layer, followed by a second outer ground plane layer.

For example, FIG. 15A is a perspective exploded view of a tri-plate stripline module **1500** for implementing a two-by-four beam forming network similar to the circuit shown in FIG. 6A-C. To create the tri-plate stripline structure, a first dielectric cover **1501** with an outer ground plane **1502** has been added over a first microstrip circuit board **1503**, which typically includes a dielectric PC board with a stripline circuit **1504** (shown in FIG. 15C) on one side and a ground plane **1505** adhered to the other side. In addition, a second dielectric cover **1506** with an outer ground plane **1507** has been added over a second microstrip circuit board **1508**, which typically includes a dielectric PC board carrying a stripline circuit **1509**. That is, the tri-plate stripline module **1500** contains an equivalent of the two-by-four beam forming network similar to the circuit shown in FIG. 6A-B (represented by elements **1503** and **1508** in FIG. 15A) with additional dielectric covers **1501** and **1506**, which each have outer ground

planes **1502** and **1507**, respectively. The additional dielectric cover with an outer ground planes shield the stripline circuits from radiating losses and interference. FIG. 15C shows a side view of layer **1503** carrying the first stripline circuit **1504**, FIG. 15C shows a side view of layer **1508** carrying the second stripline circuit **1509**, FIG. 15B shows an assembled perspective view of the tri-plate stripline module **1500**.

In this particular module, the first stripline circuit **1504** shown in FIG. 15C is similar to the microstrip circuit **610** of the two-by-four beam forming network similar to the circuit shown in FIG. 6B except that the lengths and widths of the stripline segments are adjusted to account for the different dielectric exposed to the stripline segments (i.e., air on one side of the stripline segments and a dielectric substrate on the other side of the stripline segments in the embodiment of FIG. 6A-C, versus a dielectric material on both sides of the stripline segments in the embodiment of FIGS. 15A-D). Similarly, the second stripline circuit **1509** shown in FIG. 15B is similar to the microstrip circuit **612** of the two-by-four beam forming network shown in FIG. 6C except that the lengths and widths of the stripline segments are adjusted to account for the different dielectric exposed to the stripline segments. Those skilled in the art will understand how to adjust the lengths and widths of the stripline segments to account for this change in the effective dielectric constant for the segments. Although this particular module implements a two-by-four beam forming network, any of the double-sided stripline circuits described in this specification may be implemented in a similar tri-plate stripline configuration.

FIG. 16A is a functional block diagram of a two-by-one diplexer filter circuit **1600**, which includes two-by-two quadrature hybrid junctions **1602** and **1604**, along with phase offset shifters **1606** and **1608** and a length of transmission line **1610** that is producing an additional signal delay in one signal path. FIG. 6B is a circuit board layout diagram of a back side portion of a double-sided, edge-mounted stripline signal processing module **1620** implementing the two-by-one diplex filter circuit shown in FIG. 16A, and FIG. 16C is a circuit board layout diagram of the front side portion **1622** of that circuit. The diplexer filter circuit **1600** can be implemented on a PC board module constructed from the same materials and having smaller dimensions as the two-by-four beam forming network **500** described above with reference to FIGS. 5A-C. In other words, these circuits may be manufactured in an identical manner except that the stripline circuitry is slightly different, as appropriate to implement a different circuit.

In view of the foregoing, it will be appreciated that present invention provides significant improvements in stripline signal processing network design. It should be understood that the foregoing relates only to the exemplary embodiments of the present invention, and that numerous changes may be made therein without
5 departing from the spirit and scope of the invention as defined by the following claims.